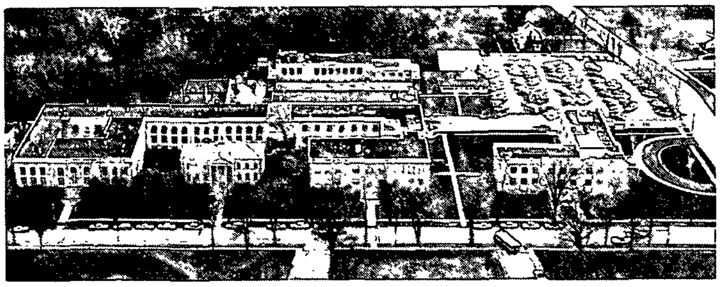

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AN INVESTIGATION OF THE ELASTIC AND DIELECTRIC ANISOTROPY OF PAPER

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An investigation of the elastic and dielectric anisotropy of paper

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ABSTRACT

The effects of fiber orientation and drying restraint on the elastic and dielectric properties in the three principal directions of paper were studied. Both variables affected the in-plane elastic anisotropy by similar magnitudes. Wet straining, however, has the greatest effect in the z-direction. The z-direction stiffness was reduced 50% by a moderate 2.4% wet strain in the plane of the sheet. The dielectric anisotropy was affected little by wet straining. The dielectric results could be explained in terms of mixture theories. The anisotropy in the dielectric constant, measured at microwave frequencies, could largely be explained as the result of fiber orientation alone, without having to assume that the fiber itself has an anisotropic dielectric constant. The elastic and dielectric results indicate that the mechanism by which wet straining enhances the elastic anisotropy does not involve fiber reorientation in the direction of straining. The in-plane dielectric anisotropy measured at microwave frequencies could be used as a measure of the fiber orientation distribution in the sheet. Based on the results presented here, this measurement should be quite insensitive to any stresses imposed on the sheet during drying.

Introduction

A material is said to be anisotropic if it exhibits properties that have different values when measured in different directions. If the material has three mutually perpendicular planes of symmetry, it is said to be orthotropic. In an idealized sense, machine-made paper is an orthotropic material with the x, y, and z principal axes corresponding to the machine, cross-machine, and thickness directions, respectively. (See Reference 1.)

The in-plane anisotropy is the result of two effects that occur on the paper machine. On the wet end, flow patterns tend to preferentially align fibers in the x-direction. In the press section and between dryer sections, the web may be stretched in the x-direction, and during drying a greater amount of tension is applied in the x-direction than in the y-direction.

The effect of fiber orientation and/or drying restraints on the in-plane elastic and strength anisotropy of paper has been the subject of many investigations (2-15). In most of these both fiber orientation and increased drying restraint in the x-direction tended to increase the measured mechanical properties in that direction, while reducing the values of these properties in the y-direction. Generally, the elastic modulus depends strongly on both fiber orientation and drying restraint. The tensile strength also depends on both variables but is usually more strongly affected by fiber orientation.

Paper exhibits anisotropy with respect to its dielectric constant (16-19). In addition to the orientation of the paper specimen, the dielectric constant depends on the measuring frequency, temperature, moisture content, and apparent density. It was suspected that at microwave frequencies, the in-plane anisotropy of the dielectric constant of paper depended only on the orientation of the fibers and not on the amount of restraint applied during drying. One objective of this investigation was to determine if the observed dielectric anisotropy in paper was the result of fiber orientation only. A second objective was to determine the effects of fiber orientation and drying restraints on the elastic and dielectric anisotropy in the three principal directions of the paper.

Dielectric constant measurements can be made in all three directions of a sheet of paper without much difficulty. Measurements of the elastic moduli in the z-direction, however, are quite difficult by conventional methods. Mann et al. have recently described ultrasonic techniques by which it is possible to determine the nine elastic constants for paper (1). Utilizing these methods, measurements of the z-direction moduli can be made relatively easily.

It was hoped that, together, the elastic and dielectric data would help explain the underlying mechanisms for the effects of drying paper under restraint.

Experimental Program

All sheets were made from a western softwood bleached kraft pulp obtained in dry-lap form. The pulp was soaked, defibered, and beaten in a laboratory Valley beater to a freeness of about 500 mL CSF. Sheets with random fiber orientation in the plane were formed on an eight-inch-square screen in a Noble and Wood sheet mold. Two sets of oriented sheets, designated "low" and "high," were formed using a "Formette Dynamique" sheet machine (20). The Weyerhaeuser Company generously allowed the use of their machine for making these oriented sheets.

Since accurate z-direction measurements require thick sheets, all of the sheets were formed with a basis weight of about 0.40 a.d. kg/m^2. These oriented sheets were formed in a single layer on the Formette with little difficulty. The random sheets, however, were formed by wet pressing together six sheets, each with a basis weight of about 0.065 a.d. kg/m^2.

It is well known from a theoretical as well as a practical standpoint that paper properties are a function of the final apparent density of the sheet. Since the process conditions adjusted to produce sheets with different fiber orientations and drying restraints resulted in changing the apparent density as well, it was necessary to include apparent density as a variable. The apparent density was varied by applying different wet pressing pressures with a platen type press.

After wet pressing, the sheets were dried under one of three levels of controlled restraint. The lowest level involved clamping the sheet biaxially using two pairs of line-type clamps and drying it without allowing any dimensional change, controlled to within about 0.1% strain. The edges of the sheet were not dried before clamping, as some researchers have done (4,5,7,15). For the medium and high levels of restraint, the sheet was clamped in the x-direction and strained while still wet to about 1.2% and 2.4%, respectively, at a rate of about 0.8% per minute. When strained in the x-direction, the wet sheet contracted in the y-direction. After wet straining, the sheet was also clamped in the y-direction, allowing no further dimensional change during drying. The stresses induced by the sheet as it dried were measured in both the x and y-directions.

After drying, the sheets were tested in a controlled environment of 23°C and 50% RH. Ultrasonic techniques were used to obtain values for seven of the nine orthotropic elastic constants of each sheet. In the plane of the sheet, values for the two Young's moduli, E_x and E_y, the shear modulus G_{xy}, and the Poisson ratios υ_{xy} (and υ_{yx}) were obtained. In the z-direction, a value for the longitudinal stiffness, C_{33}, was determined with good precision. Values were also obtained for the shear stiffnesses C_{44} and C_{55}; however, these values had considerably more scatter than those obtained for C_{33}.

Values for the in-plane Young's moduli were also obtained from tests performed on each sheet using an Instron Universal Testing Machine. In addition, the tensile strengths in the x, y, and z-directions were measured. The compressive strengths in the x and y-directions of the oriented sheets were determined using an STFI compressive strength tester.

The complex dielectric constant was measured in each of the three principal directions of the sheet. These measurements were made at 9.6 GHz, also in a controlled environment of 23°C and 50% RH, using an apparatus described elsewhere (16).

Results

The values of Young's modulus in the x-direction, E_x, measured using ultrasonic techniques are illustrated in Fig. 1. The results are plotted against apparent density, with different symbols used to indicate the three levels of fiber orientation and the lowest and highest levels of wet straining.

[Fig. 1 here]

Young's modulus depends strongly on all three variables: apparent density, fiber orientation, and wet straining. At an apparent density of 650 kg/m^3, the modulus increases about 70% in going from the randomly to the most highly oriented sheet. At each level of fiber orientation, wet straining increases the modulus by an additional 30%.

The values of Young's modulus measured in the y-direction, E_y, are shown in Fig. 2. As more fibers are oriented in the x-direction, the modulus in the y-direction decreases. The y-direction modulus is further decreased by wet straining in the x-direction.

[Fig. 2 here]

The elastic anisotropy induced in the plane of the sheet by fiber orientation and wet straining was examined. The in-plane elastic anisotropy may be defined as E_x/E_y. The effect of fiber orientation and wet straining on E_x/E_y is given in Table I.

[Table I here]

From Table I it is evident that both fiber orientation and wet straining affect the in-plane anisotropy by comparable magnitudes. With no wet straining, one can increase the anisotropy ratio from 1.0 to 3.4. With wet straining, the highest fiber orientation level, the anisotropy ratio is increased from 3.4 to 6.0.

The two in-plane Young's moduli measured using the Instron device gave similar results, although there was more scatter in the data. In fact, a simple linear relationship between the moduli determined by these two methods was observed.

The values of tensile strength measured in the x-direction are plotted in Fig. 3. The dependence of the tensile strength on apparent density, fiber orientation, and wet straining is qualitatively the same as that of Young's modulus in the x-direction. Wet straining has less of an effect on the tensile strength, however, than it does on Young's modulus. At the average apparent density of 650 kg/m^3, fiber orientation increased the tensile strength about 80% in the x-direction, whereas wet straining increased it about 18%. In the y-direction the tensile strength was reduced as fibers became more aligned in the x-direction and was further reduced with wet straining in the x-direction. This behavior is similar to that of Young's modulus in this direction.

[Fig. 3 here]

The compressive strength was measured only on the oriented sheets. The results in the x-direction are illustrated in Fig. 4. Both fiber orientation and wet straining have a smaller effect on the compressive strength than on the tensile strength. In going from zero to the highest level of wet straining, the compressive strength in the x-direction increased about 12%. In going from the low to high levels of fiber orientation, the compressive strength increased about 20%. The compressive strength in the y-direction decreased with increasing fiber orientation and wet straining in the x-direction. Again, these trends are similar to those observed for Young's modulus and tensile strength in the y-direction.

[Fig. 4 here]

Perhaps the most interesting result is the dependence of the z-direction properties on the degree of wet straining in the plane of the sheet. The stiffness coefficient*, C_{33}, measured using ultrasonic techniques, is plotted versus apparent density in Fig. 5. Because the levels of wet straining were slightly different for the random sheets than for the oriented sheets, only values measured on the oriented sheets are plotted in the figure. The stiffness C_{33} in Fig. 5 depends very strongly on the apparent density. What is more surprising, however, is the strong dependence on the degree of wet straining induced in the plane of the sheet. In going from zero to 2.4% wet strain in the x-direction, the stiffness C_{33} was reduced by half at the average apparent density. The stiffness C_{33} was only slightly affected by the fiber orientation.

[Fig. 5 here]

*Young's modulus in the z-direction, E_z, can be found from C_{33}, but measurements of C_{13} and C_{23} would also be required. Since these were not determined, C_{33} must be used. Based on results on other samples for which all nine orthotropic elastic constants were determined, E_z would be expected to have a magnitude of about 90 to 95% of C_{33}.

Schulz (3) and Parsons (6) noted that the z-direction strength tends to decrease when the sheet is wet strained in the plane of the sheet. The z-direction tensile strength was also measured on these sheets, and an approximately linear relationship was observed between this value and the measured stiffness, C_{33}.

The measured dielectric constants were strong functions of the apparent density of the sheet. In fact, very careful procedures had to be followed in determining these constants in order to yield reproducible and consistent results. The variations due to apparent density differences could otherwise easily mask the effect of fiber orientation or wet straining.

The effect of fiber orientation compared with the effect of wet straining on the anisotropy of the in-plane dielectric constants is best evaluated by examining the ratio $(\varepsilon_x' - 1)/(\varepsilon_y' - 1)$; ε_x' and ε_y' are the real components of the complex dielectric constant measured in the x and y directions, respectively. Table II was prepared using all the measured in-plane constants (51 observations). The numbers in the table are values for the anisotropy calculated from a multiple linear regression analysis of the data.

[Table II here]

From the table it is evident that although wet straining has a statistically significant effect on the dielectric anisotropy, it is small compared with the effect of fiber orientation. The relative effect of fiber orientation compared with the effect of wet straining, in the range of variables investigated, is about 10:1.

The anisotropy observed in the dielectric constant as a result of fiber orientation could be due to two effects. If the fiber itself is anisotropic, and if it has a larger dielectric constant along the fiber, then alignment of the fiber would result in a large dielectric constant in the direction of alignment without regard to the shape of the fiber. On the other hand, mixture theory relationships predict that since the fiber is long and slender, and because there are many air voids in typical paper, anisotropy would be predicted as a function of fiber orientation even if the fiber itself were completely isotropic.

Davies (21) presented equations explicitly predicting the dielectric constant of a mixture of infinite isotropic rods randomly oriented in a plane. Starting from an earlier point in his analysis, equations were derived to predict the anisotropy of a mixture of isotropic rod-shaped inclusions, embedded in air, with an arbitrary distribution in the plane (22).

A fiber segment length, weighted angular orientation distribution, was measured on a few of the random and oriented sheets. A digitizing tablet and an APPLE minicomputer were used. From this measured distribution, a theoretical anisotropy was calculated, assuming paper to be a two-phase mixture of thin isotropic rods in air. The actual measured anisotropies are compared with the results of the theoretical calculations in Table III.

[Table III here]

These results indicate that the measured in-plane dielectric anisotropy can be largely explained on the basis of the geometric arrangement of the fiber segments alone. It is not necessary to assume that the fiber itself has an anisotropy dielectric constant.

Conclusions

On the basis of the results presented here, as well as arguments and results presented in more detail in the original work (22), the following conclusions are made.

The increases observed in the mechanical properties in the x-direction as a result of wet straining are most likely due to small structural changes in the geometry of the fibers in the sheet. Specifically, the fibers oriented in the direction of wet straining are probably somewhat straightened, such that upon later application of a load, the fibers respond more equally, resulting in a stiffer and stronger sheet in that direction. The straightening of the fibers probably occurs almost entirely in the z-direction; that is, the amount of fiber undulation in the z-direction is reduced.

Concurrent with a small straightening of the fibers with wet straining is a general disruption of the sheet. The decrease in final sheet apparent density, plus the marked decrease in z-direction stiffness and strength at a given apparent density, all suggest that some fiber-to-fiber bonds are being broken or, perhaps more accurately, fewer bonds are permitted to form when the sheet is wet strained. Thus the advantages of the increase in mechanical properties in the x-direction with wet straining may very well be offset by the significant reduction of these properties in the other two directions, particularly in the z-direction.

The dielectric constants measured at microwave frequencies depended on apparent density and fiber orientation in a manner consistent with simple mixture theories. It is important to note that the dependence of the dielectric constant on fiber orientation could be described largely on the basis of the fiber geometry alone, without having to assume that the fiber itself has an anisotropic dielectric constant. Wet straining had only a small effect on the dielectric anisotropy compared to fiber orientation. On the basis of these results, together with the results of the elastic measurements, one may conclude that the mechanism by which wet straining enhances the elastic anisotropy does not involve a large fiber reorientation. The small effect of wet straining on the dielectric anisotropy is consistent with the mechanism thought to be occurring when the sheet is wet strained.

The dielectric results of this study have an immediate practical significance. On the basis of this work, it appears that the dielectric constant anisotropy measured at microwave frequencies could provide a measure of the fiber orientation in the sheet that is quite independent of the stresses induced during drying. This could be useful in the laboratory or on the paper machine. In the laboratory, it could provide a measure of fiber orientation without having to count dyed fibers in the sheet. On the paper machine, for example, it might provide valuable information relating to the control of the jet-to-wire speed ratio.

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I. The in-plane elastic anisotropy ratio E_x/E_y as a function of fiber orientation and wet straining

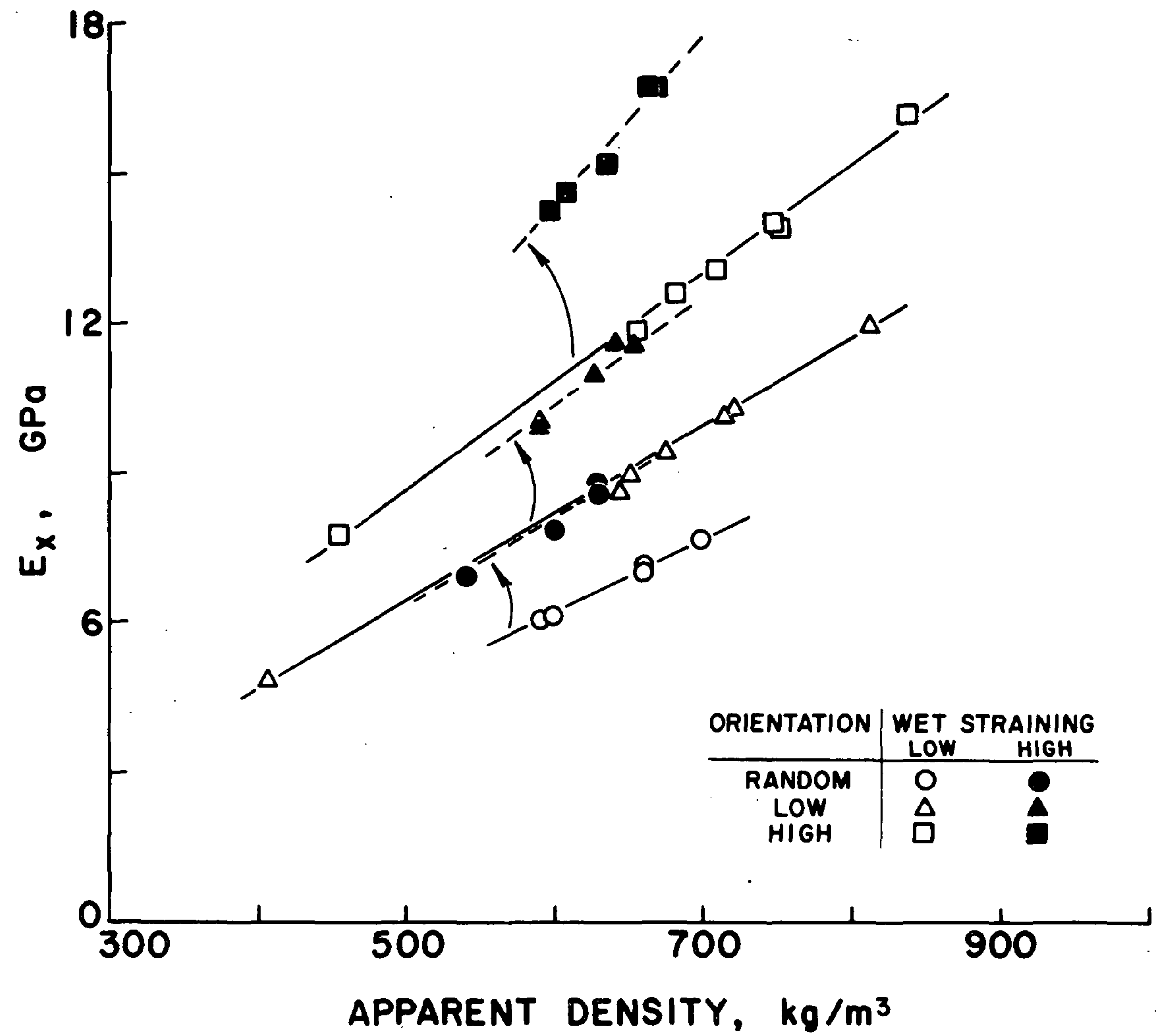
Wet Strain	Fiber Orientation		
	Random	Low	High
Low	1.00	1.67	3.41
Medium	1.24	2.09	4.55
High	1.51	2.55	5.98

II. The dependence of the in-plane dielectric anisotropy ratio $(\varepsilon_x' - 1)/(\varepsilon_y' - 1)$ on fiber orientation and wet straining

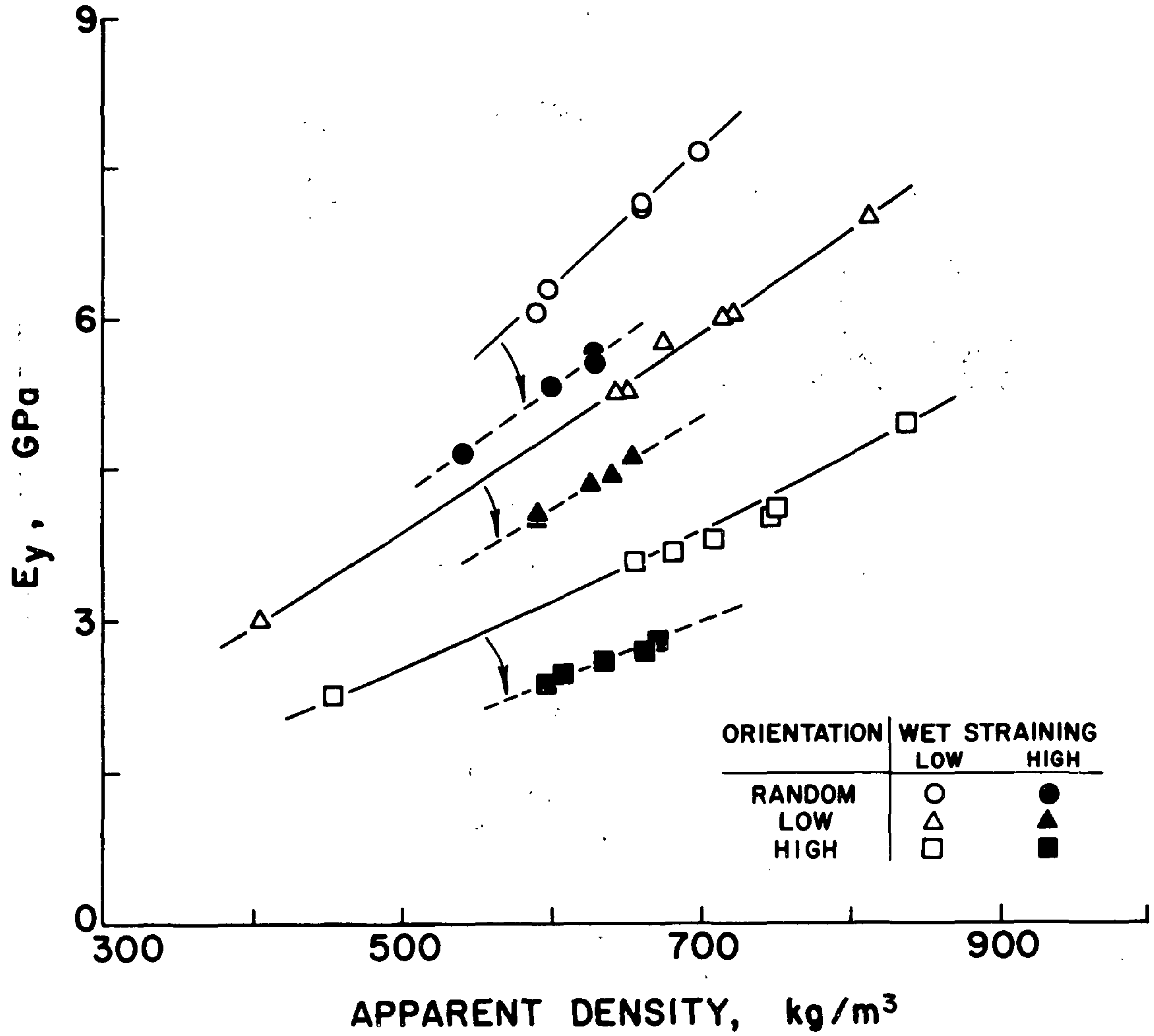
Wet	Fiber Orientation		
Medium	Random	Low	High
Low	1.00	1.09	1.19
Medium	1.00	1.09	1.20
High	1.01	1.10	1.21

III. A comparison of the measured in-plane dielectric anisotropy with that predicted by Davies, (21) mixture relationship

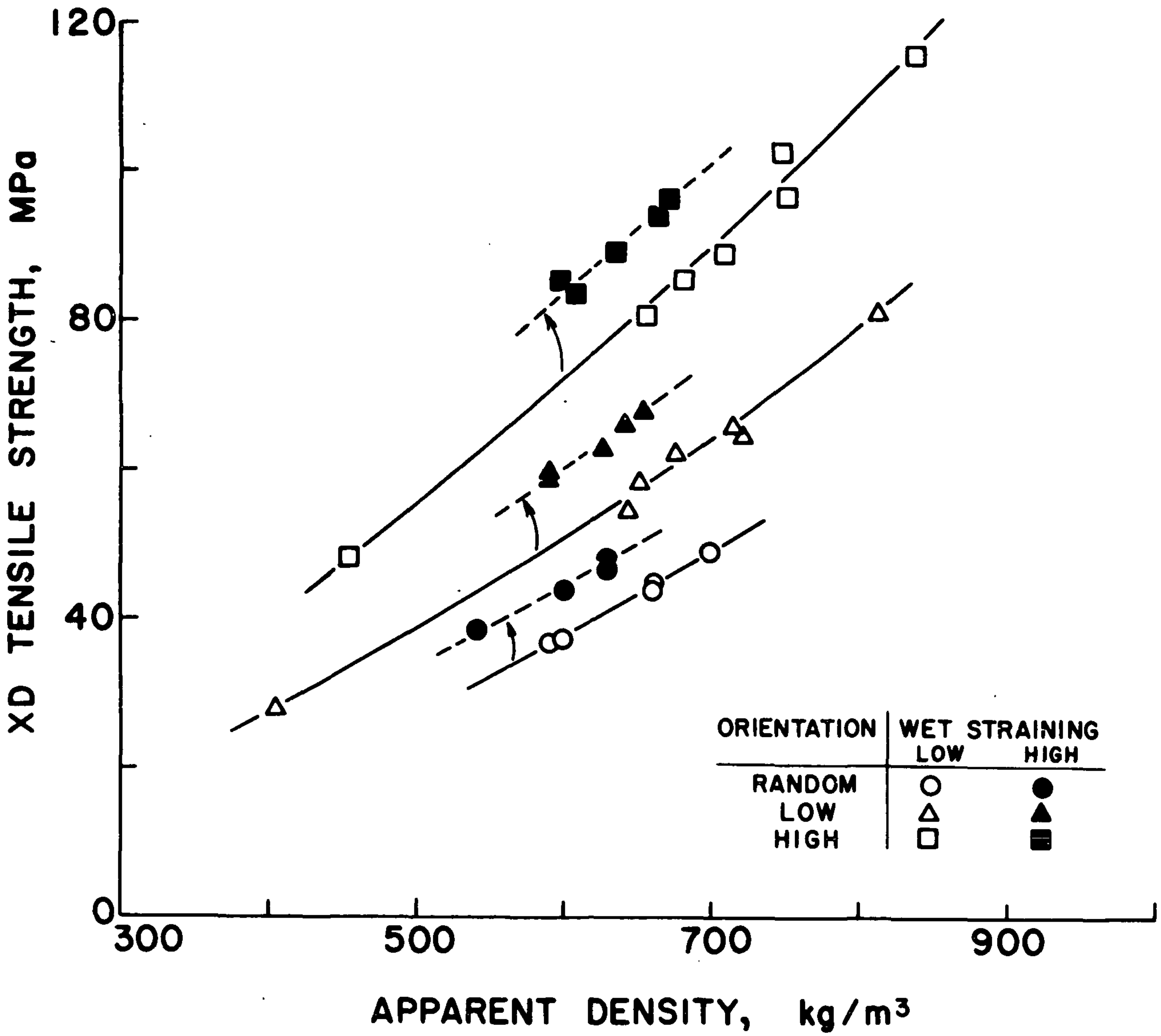
$(\varepsilon_x' - 1)/(\varepsilon_y' - 1)$	Fiber Orientation		
	Random	Low	High
Measured	1.00	1.09	1.19
Predicted	1.00	1.08	1.17



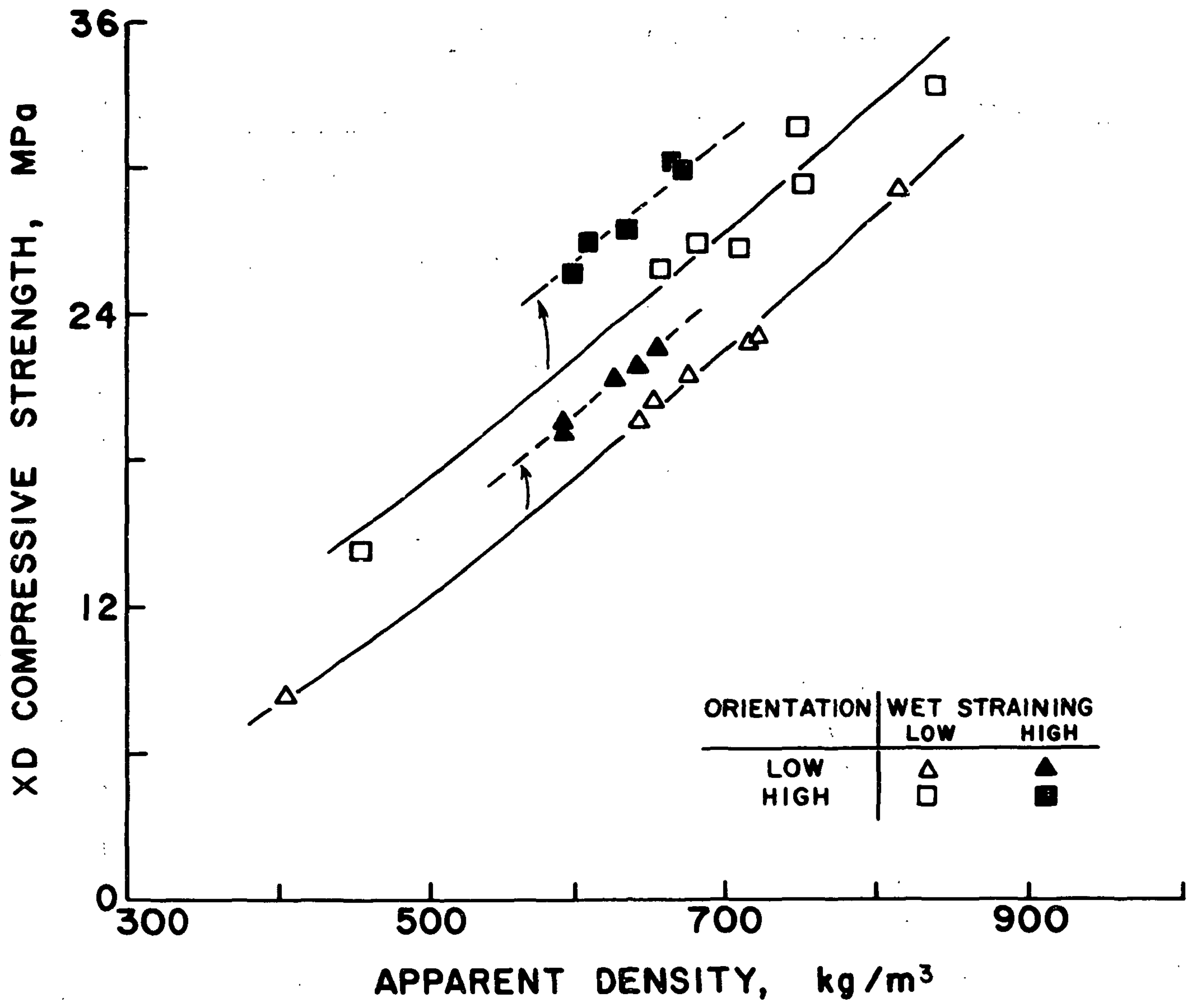
1. The dependence of Young's modulus in the x-direction on apparent density, fiber orientation, and wet straining, measured using ultrasonic techniques



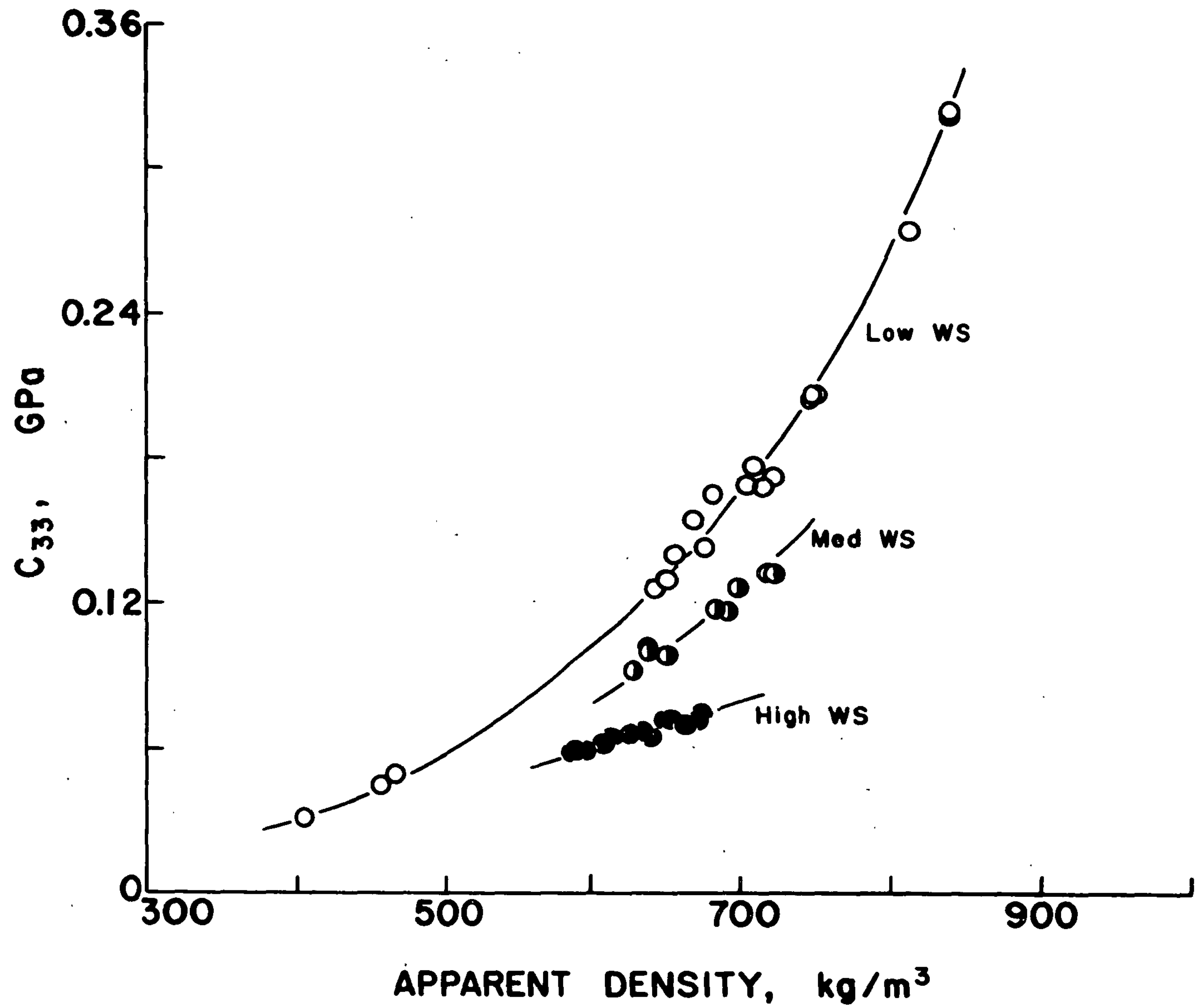
2. The dependence of Young's modulus in the y-direction on apparent density, fiber orientation, and wet straining, measured using ultrasonic techniques



3. The tensile strength measured in the x-direction



4. The compressive strength measured in the x-direction



5. The dependence of C_{33} on apparent density and wet straining for oriented sheets